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ART. XXX.—*Recent Changes in the Elevation of Land and Sea in the Vicinity of New York City*; by GEORGE W. TUTTLE.

THE late Professor George H. Cook, long identified with the Geological Survey of New Jersey, read an important paper at the Montreal meeting of the American Association for the Advancement of Science, August 13th, 1857, "On the subsidence of the land on the seacoast of New Jersey and Long Island,"* in which he stated that "an attentive examination of these facts has led me to the conclusion that a gradual subsidence of the land is now in progress throughout the whole length of New Jersey and Long Island, and from information derived from others I am inclined to think that this subsidence may extend along a considerable portion of the Atlantic coast of the United States."

The evidence on which Professor Cook based this conclusion was mainly of a geologic nature, and consisted of, 1st, submerged forests and buried timber found in the marshes and along the coast below tide level; 2d, numerous Indian shell heaps which have been found below tide level; 3d, the extension of the marsh on the upland, verified by many old residents, and by the dying out of cedar trees on the margin; 4th, less fall of water at any stage of the tide available to operate the waterwheels of mills on tidal streams near the sea.

It was the opinion of a number of mill operators, that within their memory the loss of head available to operate their wheels was of such an amount as would denote the sinking of the land at the rate of two feet per century. Besides, sluices in banks protecting meadow land, built about 150 years ago, were found three feet below tide level and useless for their intended purpose.

Professor Cook's estimate of the amount of subsidence of the

* This Journal, 2d Series, xxiv, 1857, p. 341.

land, which has been quoted by many authorities, rests on the above evidence, and is manifestly open to doubt and uncertainty, as he recognized when he wrote in his 1885 report, that "we find conclusive evidence of a general subsidence of the coast, or rise of water level to an extent of from ten to twenty feet within a short period of geologic time, but at a rate which is not quite definitely established." Professor Cook furthermore stated in his report of the Geology of New Jersey in 1868, that "this movement is one of a series which has occurred on our coast by which the line of water level has been alternately elevated and depressed, the whole range being confined within twenty feet."

Others have since frequently expressed the same ideas, but as they probably made use to a large extent of Professor Cook's opinions and evidence, it will be needless to quote them.

The self-registering tide gauge had only recently been made use of when Professor Cook read his paper, and tidal observations could not be obtained to determine the rate of subsidence, but since that date long series of tidal observations have become available, and it is proposed to develop in this paper what such observations in New York Harbor can tell as to the relative changes in the elevation of earth and sea in the vicinity.

The tidal observations at New York, which are of importance, start from the year 1853, when a self-registering tide gauge was put in operation by the Coast Survey at Governor's Island, and maintained up to and including the year 1879, when the series terminated. We also have the records of a self-registering gauge maintained by the Coast and Geodetic Survey during the years 1876-92, at Sandy Hook, N. J., records of self-registering gauges of the Department of Docks and Ferries from 1888-1903, at Pier A, West 57th St., and from 1894-1903 at East 24th st., in New York City, besides the record from a self-registering tide gauge of the Coast and Geodetic Survey at Fort Hamilton, for the years 1893-1902.*

The observations at Governor's Island were all referred to B. M.,† which was established about the year 1853 by the Coast Survey and is still in existence. Levels were run from this bench mark to other benches, in 1875 and again in 1886. The differences found at those times were checked in 1898 and 1900 and found correct, so that we may be confident that since 1875 B. M., has not settled or been otherwise disturbed.

The datum plane used in this paper is mean low water—

* The writer is indebted to the U. S. Coast and Geodetic Survey and to the Department of Docks and Ferries, New York City, for tidal data not hitherto published.

† For description see C. and G. S. Report 1887, app. 14, p. 293.

" " 1899, app. 8, p. 555.

M. L. W.—at the Battery as used by the Department of Docks and Ferries which is known as Battery datum, and is 2·186 feet below the datum plane of the Coast and Geodetic Survey in their levelling operations in the vicinity of New York City.*

The elevation of B. M., from the above Coast and Geodetic Survey levels is 14·203 feet, and from ordinary levels run directly from the Battery to Governor's Island the elevation 14·160 was obtained. We shall adopt the former value in the succeeding work.

The following is the record of the observations at Governor's Island for each year.

Year.	Half tide level above zero of staff.	Half tide level above Battery datum.	
1846	8·32 ft.	----	
1847	10·31	----	
1848	13·12	----	
1849	12·92	----	
1850	14·16	----	
1851	12·20	----	
1852	10·51	----	
1853	5·30	1·920 ft.	} Probable elevations
1854	5·07	1·690	
1855	5·32	1·940	
1856	7·507	1·778	
1857	7·640	1·911	
1858	7·591	1·862	
1859	7·616	1·887	
1860	7·575	1·846	
1861	6·580	1·921	
1862	6·494	1·835	
1863	6·498	1·839	
1864	6·570	1·911	
1865	6·476	1·817	
1866	6·468	1·809	
1867	6·615	1·956	
1868	6·557	1·898	
1869	6·435	1·776	
1870	4·620	1·961	
1871	4·472	1·813	
1872	4·468	1·809	
1873	4·516	1·857	
1874	4·358	1·699	
1875	4·40	1·741	
1876	4·46	1·801	
1877	4·56	1·901	
1878	4·68	2·021	
1879	4·64	1·981	

* See appendix 14, Report of Coast and Geodetic Survey, 1887.

The above series of tidal observations from 1870–79 were carefully examined for use in determining the mean sea level—M. S. L.—in New York harbor* and these values resulted:

Year.	Mean sea level above zero of staff.	Mean sea level above Battery datum.
1870	4·692 ft.	2·033 ft.
1871	4·545	1·886
1872	4·533	1·874
1873	4·612	1·953
1874	4·410	1·751
1875	4·505	1·846
1876	4·540	1·881
1877	4·630	1·971
1878	4·751	2·092
1879	4·688	2·029

The zero of the tide staff at Governor's Island was found by levelling to be 16·899 ft. below B. M., in 1871–2 and 16·826 in 1875. Consequently the mean of these two values, 16·862 ft., has been adopted as the correct value for the series of observations 1870–79.

The elevations of half tide level†—H. T. L.—from 1853 to 1869 are subject to considerable uncertainty owing to changes in the elevation of the zero of the tide staff, of which no record appears to have been made. Such changes must have taken place in 1856, 1861, and 1870. In 1853 the zero of the tide staff was recorded as 17·00 ft. below B. M., but this location does not harmonize with the succeeding observations and there is much evidence to contradict it.

We determine the probable elevations of H. T. L. at Governor's Island for the years 1861–69, by making the average H. T. L. for the four years 1866, '67, '68, and '69 have the same elevation as the average for the four years 1870, '71, '72, and '73: the elevations of H. T. L. for the years 1856–60 are fixed by giving the average of the observations for 1857, '58, '59, and '60, the same elevation as those of 1861, '62, '63, and '64; and finally we make the average H. T. L. for the three years 1853–55 the same as the average of the three years 1856–58. Very nearly the same values are arrived at if we start with the elevation 14·51 ft. of B. M., above M. L. W. given in the Coast Survey Report for 1853. We also observe that the series of 1861–1869 shows no tendency toward increased elevation with the time, and for that reason they seem to confirm our location of the 1853–55 observations.

These elevations are still further shown to be the most probable ones, from the fact that in 1879 the elevation of B. M.,

* Coast and Geodetic Survey Report for 1899, p. 404.

† Which is the average of high and low tides.

was given as 14.6 ft. above M. L. W. "from the observations of 1853 verified in 1873"; and that the observations of H. T. L. at Boston from 1853-5 and 1870-3 have substantially the same relative elevations and yearly fluctuations.

From October 2d to 30th, 1886, a series of comparative tidal observations were carried out at Governor's Island and Sandy Hook, and the resulting M. S. L. corrected for annual inequality above zero of staff at Governor's Island was 4.200 ft., with zero of staff at that time 16.43 ft. below B. M., making M. S. L. 1.973 ft. above Battery datum.

We next have the tidal observations at Sandy Hook, which are as follows:

Year.	M. S. L. and H. T. L. above Sandy Hook datum.		Equivalent H. T. L. at Governor's Island above Battery datum.
1876	6.74	M. S. L. from hourly heights	1.774
1877	6.90		1.934
1878	7.06		2.094
1879	6.87		1.904
1880	6.84		1.874
1881	6.89	H. T. L. from high and low waters (values in parenthe- sis partly estimated)	1.924
1882	6.90		1.934
1883	7.02		2.054
1884	(7.17)		2.204
1885	(6.82)		1.854
1886	(6.90)	M. S. L. from hourly heights	1.934
1887	6.91		1.944
1888	7.00		2.034
1889	7.13		2.164
1890	7.05		2.084
1891	7.09		2.124
1892	7.05		2.084

The observations made at Sandy Hook were referred to a plane 17.63 below B. M. T.,* and are reduced to Battery datum by means of the simultaneous observations for the four years 1876-1879 at Governor's Island and Sandy Hook.

While spirit levels have been taken between Sandy Hook and Governor's Island, yet, owing to the considerable distance of the run, they are probably in error more than levels derived from the simultaneous tidal observations.

The levels derived from the four years of tidal observations agree almost precisely with the levels obtained from the simultaneous tidal observations in October, 1886, and are more suitable to reduce the Sandy Hook observations to simultaneous ones at Governor's Island than the spirit levels. From the spirit levels of 1887 as revised in 1899, the elevation of B. M.

* Described in C. and G. S. Report for 1887, appendix 14.
" " " 1899, page 472.

Governor's Island, above B. M. T. Sandy Hook was 1.361 ft., while from the simultaneous tidal observations of October, 1886, the difference was 1.468 ft., and from the tidal observations of 1876-9, 1.472 ft. This latter difference has been adopted in the reduction.

The observations at Sandy Hook have to be reduced to the equivalent values of half tide level at Governor's Island, which for the ten years 1870-79 was .067 ft. lower than mean sea level, and consequently the elevations have been corrected by this amount in the column "Equivalent H. T. L. at Governor's Island above Battery datum."

The tidal records at Governor's Island from 1870-79 are particularly important in this investigation, and while the observations appear to be satisfactory, the frequent change of staffs make it desirable to have an independent check on their accuracy which we have in the observations at Sandy Hook in 1876-79, taken in connection with the levels obtained from the simultaneous tidal observations in October, 1886.

We next have a series of tidal observations at Fort Hamilton, N. Y., from 1893-1902, as follows :

Year.	H. T. L. above zero of staff.	H. T. L. above Battery datum.
1893	5.815 ft.	2.067 ft.
1894	5.885	2.137
1895	5.785	2.037
1896	5.875	2.127
1897	5.945	2.197
1898	5.960	2.212
1899	5.955	2.207
1900	5.820	2.072
1901	6.030	2.282
1902	6.085	2.337

The zero of the gauge at Fort Hamilton was 42.194 ft. below B. M. L. (destroyed in 1901), and 17.951 ft. below B. M., at Governor's Island, according to the Coast and Geodetic Survey levels of 1887. Two independent determinations of this difference in elevation have since been made, one in 1898 of 17.971 ft., and in 1900 of 18.019 ft. The 1887 value has been adopted, however, in the reduction of the staff readings to Battery datum.

Besides the above observations of the Coast and Geodetic Survey, we have the following tidal records of the Department of Docks and Ferries, all referred to Battery datum.

Diagram showing the yearly averages of Half Tide Level at New York City and the corresponding yearly averages of the principal meteorological phenomena.

	Half tide level above Battery datum.		
	Pier A.	West 57th St.	East 24th St.
1889	2·273 ft.	2·079 ft.	----
1890	2·063	1·990	----
1891	2·012	2·082	----
1892	1·910	1·902	----
1893	2·232	2·075	----
1894	2·133	2·075	2·164 ft.
1895	2·265	2·018	2·067
1896	2·314	2·003	2·053
1897	2·359	2·212	2·173
1898	2·258	2·278	2·301
1899	2·230	2·245	2·127
1900	2·250	2·127	2·012
1901	2·514	2·461	2·274
1902	2·490	2·492	2·361
1903	2·343	2·433	2·295

The yearly averages of half tide level at New York which have been given, are plotted in the diagram on page 339. They show a continual oscillation, having an amplitude of nearly 0·3 ft., about an average value which since 1875 has uniformly increased. These oscillations when considered in relation to the accompanying meteorological phenomena, also represented in the diagram, are seen to be mainly due to atmospheric pressure and winds. They are more or less perfectly eliminated by taking the average for five or more years, and when thus eliminated the observations appear to show that mean sea level remained nearly stationary from 1853 to 1875, since which time it has been rising relatively to the land by about 1·45 ft. per century. The rate of change since 1875 may be obtained in the following different ways.

(1) From ten years' observations at Governor's Island, 1870–79, the elevation of M. S. L. was 1·932 ft., and at Fort Hamilton the average elevation of H. T. L. from 1893–1902 was 2·165 ft.; allowing 0·03 ft. as the difference between M. S. L. and H. T. L. at Fort Hamilton, we have an increase in elevation of H. T. L. of 0·26 ft. in twenty-three years, or 1·1 ft. per century.

(2) The observations at Fort Hamilton alone, give the following result by taking the average H. T. L. of the first five and last five years of the series:

H. T. L. 1893–97 elevation.....	2·108 ft.
H. T. L. 1898–1902 “	2·223

An average elevation of H. T. L. of 1·15 ft. in five years, or 2·30 ft. per century.

(3) The tidal observations at Pier A for the last ten years,

1893–1902, give 2·304 ft. as the elevation of H. T. L. at Pier A, while H. T. L. at Governor's Island 1870–79 was 1·858 ft., an increase in the elevation of H. T. L. of ·446 ft. in twenty-three years, or 1·94 ft. per century.

(4) The observations at Governor's Island 1870–79 give

Elevation of M. S. L. 1870–74 1·899 ft.

Elevation of M. S. L. 1875–79 1·964

An increased elevation in M. S. L. of 0·065 ft. in five years, or 1·30 feet per century.

(5) The observations at Sandy Hook for the seventeen years 1876–1892 give:

Elevation of M. S. L. 1876–1881 6·883 ft.

Elevation of M. S. L. 1887–1892 7·038

An increased elevation in M. S. L. of 0·155 ft. in eleven years, or 1·41 ft. per century.

(6) The observations for the fourteen years 1889–1902 at Pier A, when taken by themselves, give:

Elevation of H. T. L. 1889–1895 2·127 ft.

Elevation of H. T. L. 1896–1902 2·345

An increased elevation in H. T. L. of 0·218 ft. in seven years, or 3·1 ft. per century.

(7) The average of the observations of H. T. L. for the ten years 1870–1879 at Governor's Island, compared with all the above mentioned observations at New York for the nine years 1894–1902, shows that H. T. L. has risen ·326 ft. in twenty-two and one-half years, or at the rate of 1·45 feet per century.

(8) The Department of Docks and Ferries of New York City found it necessary in 1898 to raise their plane of mean low water (to which soundings are reduced) 0·24 ft. above that in use since 1872; and the U. S. Engineers in 1900 raised their plane of mean low water 0·32 ft. above that used in 1872.

On account of the many disturbances to which tidal observations are subject, the frequent change of tide staffs in some cases, and the settlement of bench marks, it is necessary to use considerable caution in the interpretation of the observations, and all possible checks should be used. Only when independent determinations show a reasonable agreement, can we feel sure of the result arrived at.

Besides the errors which may occur in the measurement of the elevation of mean sea level, it is subject to changes from many causes, among which may be mentioned changes in atmospheric pressure, winds, temperature, various tidal components having periodicities ranging from six hours to nineteen years, river outflow, evaporation, changes in ocean currents, melting of polar snow and ice, changes in salinity,

detritus carried into the sea by rivers, and the wearing away of shores, as well as changes in the position of the earth's axis and speed of rotation.

High and low waters only were measured in most of the observations, and consequently H. T. L., which is the mean of the above quantities, has been given in the tables, except in a few instances.

In general M. S. L. obtained from hourly ordinates, which determines a level surface, differs from H. T. L. to a small extent, depending in amount on the shape of the tide wave. In deep water this difference is usually quite small, but in shallow water, or where the tide wave is obstructed, it requires to be taken into account.

It has been computed from the tidal constants that M. S. L. is 0.01 ft. above H. T. L. at Sandy Hook, and 0.067 ft. above at Governor's Island. The differences are about the same at Pier A, West 57th st., and East 24th st., as they are at Governor's Island, so far as present information goes, and at Fort Hamilton the difference is estimated to be about 0.03 ft. The Sandy Hook observations, only, have been corrected to H. T. L. at Governor's Island in the above tables.

The settlement of bench marks would make the sea appear to rise in relation to the land by the entire amount of the settlement. Consequently all bench marks should be carefully checked to guard against any change, and this has been done in the case of B. M., and B. M. L. mentioned above.

The accuracy of the tidal averages of H. T. L. obtained from an automatic tide gauge varies somewhat with the type of the instrument employed, and the attention given to it. The results are most accurate where the tidal range is small, and the working scale of the gauge large. An examination of the yearly means of the various tidal observations goes to show that the yearly averages of half tide level should not have a probable error greater than 0.05 ft., although the maximum error may be nearly three times as great. The greater part of this probable error is due, however, not to the inaccuracy of the tide gauge, but to fluctuations of the mean sea level from meteorological causes.

When we examine the daily changes of mean sea level in New York Harbor, we find that they are mainly determined by the velocity and direction of the wind. N.W. and W. winds are the effective agents in depressing the sea level and N.E. and E. winds in raising it.* The mean level has been at times raised

* Des Barres in his charts of New York Harbor published in 1780, says, "Tides rise perpendicularly about seven ft., but are sometimes checked to such a degree by the Westerly or North Westerly winds, as to lower the water on the bar to three fathoms and one-quarter, and Easterly or North Easterly winds have frequently risen it to five fathoms."

or depressed as much as three feet from its average elevation during strong gales in the above directions.

When we pass from the daily changes to the monthly averages of mean sea level, we find a remarkable correspondence between the height of mean sea level and the movement of the northwest and west winds, while the northeast and easterly winds appear to have little effect on these monthly averages. Probably the greater and more uniform effect of the westerly winds, which has been proved by analysis for a long series of years, is due to the fact that they are the prevailing winds, last for a considerable time, have greater intensity, and are effective over large areas, while the easterly winds are more local, and changeable.

The atmospheric pressure does not usually appear to have an important share in determining the monthly values of mean sea level, except as it influences the intensity of the prevailing westerly winds.

These monthly averages show a minimum mean sea level, sharply defined in January, and a maximum mean sea level, not sharply defined in August; while the westerly winds have a maximum sharply defined in January, and a minimum not sharply defined in August. This seasonal difference in elevation of mean sea level averages 0.55 ft. By means of yearly averages we eliminate these seasonal fluctuations as well as all astronomical effects, except that having a period of 19 years, which is so small in this latitude (less than 0.2 inch) that it may be neglected.

Particularly noticeable in the tidal curves is the very considerable depression of half tide level in 1874, and the great elevation of half tide level in 1878. When compared with the curve of atmospheric pressures, it will be noticed that abnormal changes of the barometric pressure occurred in those years, which seem to show that they occasioned the tidal fluctuations.

Tidal elevations and barometric pressures at a number of stations on both sides of the Atlantic show that these atmospheric surges extended over a large area, and similarly affected all tide gauges on the North Atlantic Ocean.

In the year 1900 a marked depression in half tide level is shown by the New York observations. As this same depression was observed at Fernandina, Fla., and other points, we may presume that it took place along the entire Atlantic Coast. At New York City, it appears to have been caused by the unusual strength of the N.W. and W. winds.

In 1901 and 1902 mean sea level at New York City rose to a height not before attained, which was probably due to the low barometric pressure prevailing during those years.

As the effect of the atmospheric pressure and winds on the sea level at any place is the integral of their effects taken over a wide area, while these observations are taken at only one point, a close correspondence is not to be expected, particularly where the locality is at the junction of continental and ocean areas, as in this case.

It has been recently found from the yearly averages of atmospheric pressure at many widely separated places, that abnormal variations of atmospheric pressure occur of considerable duration, which are apparently caused by the surging to and fro of the atmosphere. They affect a very considerable area and have a tendency to recur in periods of about three and eight years, corresponding closely with periodic variations of solar energy received by the earth.

The examination of long series of tidal observations in places scattered over the world discloses very similar periodicities, which are doubtless due in the main to the surging of the barometric pressure before alluded to, and the consequent change in the atmospheric circulation.

Tidal observations from Maine to Florida disclose a striking similarity among the changes in half tide level at all localities on the Atlantic Coast, and the same phenomena have been observed on the shores of the Baltic Sea. It appears quite certain that these fluctuations of yearly half tide level, nearly alike in direction and amount, are due mainly to changes in the mean annual barometric pressure, and the accompanying changes in wind velocities. These periodic fluctuations, never more than a few years in duration and very much alike in extent and direction at all the points embraced in a large area, evidently are changes due entirely to the sea, and can in no way be considered as showing a change in the absolute elevation of the land.

On the other hand, there are no changes in the meteorological phenomena which will account for a continuous increase of half tide level for a series of years, such as have been observed at New York from 1875 to 1902, at Boston for the same period, and at Penobscot Bay from 1870 to 1885. Neither will such changes account for the continuous depression of sea level shown by the series of observations at Stockholm, Sweden, commencing in 1774, and verified by numerous observations along the Swedish coast of the Baltic Sea, where it has been found that the land has risen nearly two feet relatively to the sea, while equally reliable observations on the German coast of the Baltic Sea, dating from 1811, show no appreciable change in level.

No long period or continuous variations of atmospheric pressure, winds, temperature, ocean currents, etc., appear to exist to

explain these secular changes in mean sea level, and if such changes did occur, they could hardly explain the difference in amount and direction of the changes of sea level observed at different points. Besides, it is seen from tidal observations on the German coast of the Baltic Sea, the North Sea, and the coast of India, that no continuous change in ocean level has occurred in those places, which would probably be the case if there had been any great or long continued change in absolute ocean levels elsewhere.

We must conclude then, except for minor variations due to meteorological conditions, that it is the land and not the sea which is changing in elevation.

Most of the geological evidence appears to show that the movement of the land relatively to the sea in recent geologic times has been of a cyclic character and confined within narrow limits. There is little geologic evidence to be found in the vicinity of New York of a definite character to indicate depression. It is true that marsh sod can be found outshore from the beach, and below mean sea level; that cedar trees die out on the shore, and that peat bogs and stumps of trees have been found in many places below sea level. These phenomena are to be explained, however, by the inroads of the sea during storms, and by wave action; as well as by the compression and consolidation of the marsh land, which has been known to sink as much as three feet when drained, or loaded with sand. As we leave the shore these apparent evidences of subsidence disappear and in places thoroughly protected from the sea few or none of them are found.

It does not appear from the evidence presented by tidal records, or from historic or geologic evidence, that our sea-coast is in any immediate or serious danger from subsidence of the land, for almost without exception the longest records show the least change, and were it not for the power and efficiency of modern dredging machinery the shoaling of harbors would probably be a more serious affair.

The tidal observations have been taken for so short a time, however, that they can only tell us what has been going on recently, and do not disprove a possible change in ocean elevation too small to be detected within the period of observation.

In conclusion it may be stated with confidence, as the result of an inspection and study of tidal observations on both sides of the Atlantic for the first time brought together,

(1st) That the mean sea level oscillates in an irregular manner, having an average period of about eight years. These oscillations closely resemble one another at many ports distant from each other, and appear to be largely due to changes in

atmospheric pressure, and the resulting changes in wind velocities.

(2d) The above oscillations compensate themselves completely in the course of time, and do not give rise to a continuous movement in a given direction.

(3d) That in addition to the above movements of the sea some ports show a more or less continuous rising of the sea relatively to the adjacent land; others a lowering of the sea level in its relation to the land, and still others maintain a constant relation between the two. These latter make it clear that except for the periodic changes noted above, the sea does not change its level, and that the relative changes are due to land movements.

(4th) At various ports the rate of change in the elevation of mean sea level referred to the adjacent land has not remained constant, but has varied in a considerable degree. All the observations show that for long periods the rate of change is less than took place in some part of that period, and the evidence is strong that the movement is not continuous, but oscillatory and confined within narrow limits.

(5th) The observations at New York City show that since 1875 the land has been subsiding relatively to mean sea level by about 1.45 ft. per century, but from the establishment of the self-registering tide gauge in 1853 to that date, little or no change had occurred, and it is improbable that the present rate of subsidence will be continued indefinitely.